12-24-2022

Safety Related HVAC Systems in PWR Nuclear Power Plants

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MEMS 500

Washington University in St. Louis

December 2022

1 Abstract

This paper is for the completion of MEMS 500 - Independent Study at Washington University in St. Louis. The materials and coursework are based off MEMS 5420 HVAC Analysis and Design I. This course covered readings and problems from chapters 1-8 of *Heating, Ventilating, and Air-Conditioning Design and Analysis - sixth edition* by McQuiston, Parker, and Spitler. Topics included moist air properties, indoor environmental quality (comfort and health), heat transmission in building structures, space heating loads, and cooling loads.

This paper focuses on a few of the safety related HVAC systems found in PWR or pressurized water reactor type nuclear power plants. HVAC systems provide personal comfort and safety through heating, cooling, and ventilation air at appropriate temperatures, humidities, and flow rates for normal machine operations. Due to the sheer number and complexity of these systems, my focus is on only a few considerations. This includes an overview of each building on a campus and their HVAC needs. Special topics include a breakdown of radioactive filtration systems, and ventilation for excess hydrogen in battery rooms.

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2 Introduction

2.1 Why Nuclear Power?

In the United States, 20% of electricity generation comes from nuclear power plants [1]. Nuclear power is considered a clean energy source as it releases no harmful emissions to the environment during the energy generation process. Compared to all available resources, nuclear energy has the highest energy density and capacity factor. A capacity or generation factor is a measure of a power plants ability to maximize it's energy generation potential. For comparison, the capacity factors of nuclear power, natural gas, and hydropower are 92%, 57%, and 37%, respectively [2]. Meaning, over the course of 365 days a nuclear power plant generates energy 336 days. While a hydropower plant generates electricity 135 days of the year. It is worth noting, hydropower has the highest capacity factor of all renewable energy resources. One surprising fact is that nuclear power generation releases the least amount of radiation [3]. Still, there are legitimate concerns from the public about potential nuclear disasters such as Chernobyl or Three Mile Island. To answer these concerns the NRA has put in place new stricter safety systems. The technology inside these plants are also constantly improved by companies such as Westinghouse Electric, GE, Duke Energy, and many more. Another legitimate concern are the consequences of producing nuclear waste [3]. Despite these concerns, nuclear power is one of the most promising forms of clean energy available. In fact, it makes up half the clean energy used in the United States [1].

Unlike other sources of energy, countries don't need to utilize their own natural resources nor do they need to release harmful emissions such as carbon dioxide and greenhouse gases into the atmosphere. Not depending on fossil fuels also affords countries "energy security" by allowing them to be less dependent on foreign energy sources. [4]. In my opinion, this is incredibly relevant given recent world events such as the war in Ukraine. Nuclear energy is also relevant in the science community. On December 13, 2022 the Department of Energy released the news that there was a "breakthrough in the ignition process of nuclear fusion" [5]. On a personal level, I find energy generation fascinating and I have pursued coursework in multiple energy generation systems. This paper is an opportunity to further expand my knowledge in HVAC and another energy system.

2.2 HVAC System Operations and Equipment

HVAC stands for heating, ventilation, and air-conditioning. Since the early 1900s every new construction in the United States has a HVAC system for both personal comfort and health. This is an over-looked and under-appreciated topic of mechanical engineering. The main elements of any HVAC system are air-handling units, delivery units, heating units, cooling units, as well as ducts and pipes for transportation. There are also fans, blowers, and pumps that cause pressure differentials in the ducts and pipes encouraging fluid to move through these systems. Inside these systems are numerous pieces of vital equipment including boilers, humidifiers, cooling coils, heating coils, expansion valves, and more. Understanding that these pieces of equipment make up a HVAC system, one realizes HVAC systems are in every part of a nuclear power plant. Only systems vital to the safety of the plants are touched upon in this paper. The ultimate goal is to minimize the spread of radioactive particles as these particles degrade materials and pose serious health hazards [6]. The regulations and codes for these systems are set by organizations such as NFPA, IEEE, ASHRAE, and the NRA.

3 PWR Plants

3.1 Plant Operation

PWR or pressurized water reactor based power plants are the most common nuclear power plants in the United States, making up 65% of plants [6]. Figure 1 illustrates the systems composing a PWR plant [7]. In a PWR power plant, water is heated by passing through a pressurized vessel containing a fission reactor. This water is contained at a high pressure to ensure it does not turn into steam, hence the name "pressurized water" [8]. This hot water flows through the reactor into a steam generator, where it evaporates a second fluid. Thereby, keeping all fluid in direct contact with the reactor inside the containment structure seen in Fig. 1. The steam is then pumped into the turbine building where it rotates a turbine connected to a generator for electricity generation. This energy flows through the power grid to provide electricity. After rotating the turbine, the steam is condensed back into a liquid where it is pumped back into the steam generator. To help condense the steam into a liquid, a third water source is used. Here, water from a cooling reservoir is pumped pass the steam. The water from the cooling reservoir gains heat in the process, so it goes through cooling towers before entering back into the cold-water reservoir [8].

Overall, there are 3 loops in a PWR plant [9]. The primary loop where water is heated by the reactor within the containment structure. The secondary loop where water turns into steam for electricity generation before being condensed for re-use. Finally, the cooling loop which aids in condensing the steam for electricity generation. By having three separate loops each step in the process can be monitored and handled separately and safely. As opposed to every step in the process being intermingled which ultimately makes it more difficult to monitor, identify, and fix problems.

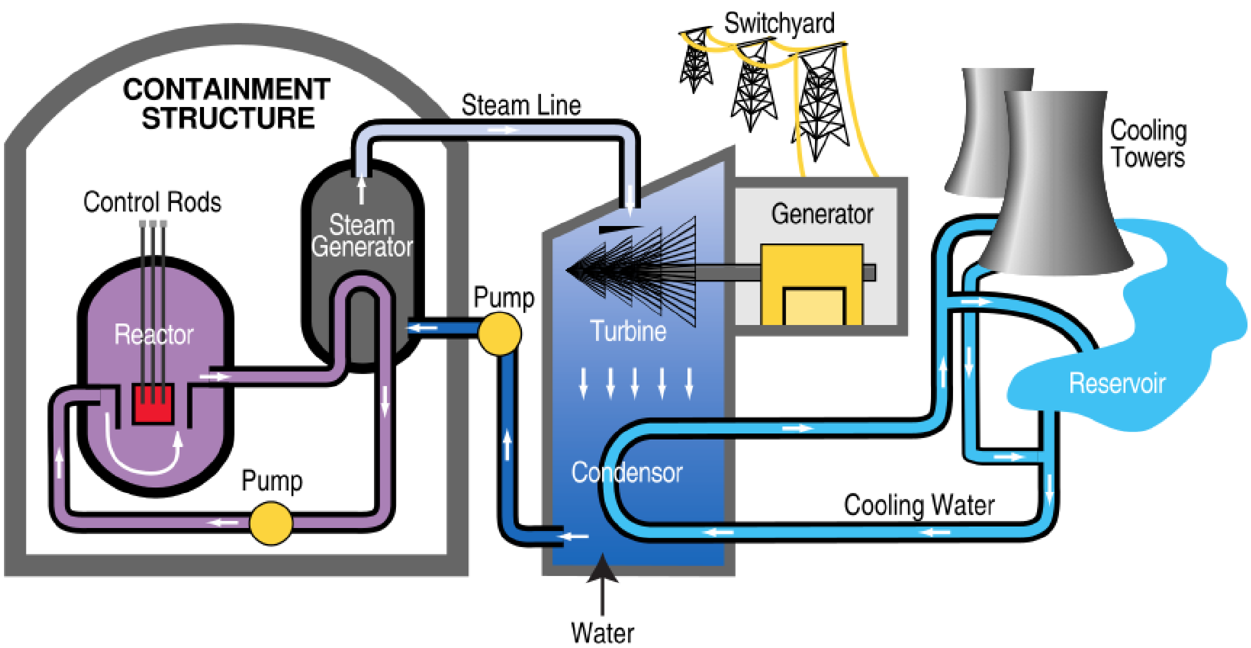


Figure 1: An illustration of a PWR nuclear power plant [7]. There are 3 loops, the containment, primary, and cooling loop [9]. The containment loop heats the primary loop water into steam, the steam rotates the turbine for electricity generation, and the cooling loop condenses the steam back into a liquid for the cycle to continue.

3.2 Site Layout and Considerations

A nuclear power plant consists of dozens of buildings. Figure 2 details a site plan of a PWR plant [10].

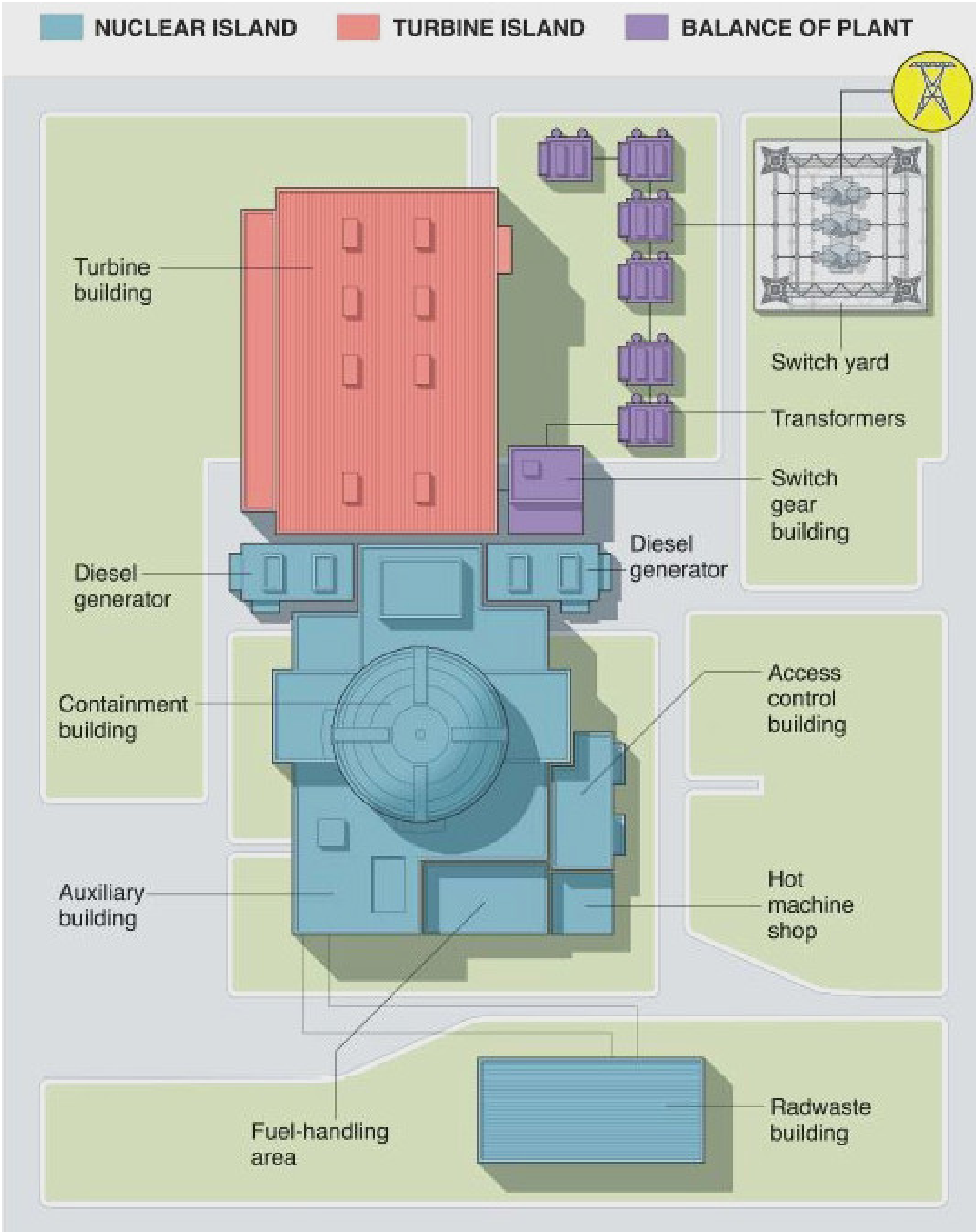


Figure 2: Site plan of a PWR nuclear power plant. The site is divided into three sections, nuclear island, turbine island, and balance of plant buildings [10].

A site can be divided into three sections: the nuclear island, turbine island, and buildings aiding in the balance of the plant. Buildings in the nuclear island operate alongside the nuclear reactor, while turbine island operates the turbine and generators. The balance of the plant buildings connect the plant to the grid and contain other miscellaneous buildings [10]. There are number of ways to divide a nuclear power plant up, but all of them have similar buildings [6]. These buildings include:

- Containment Building
- Auxiliary Building
- Control Room
- Control Spreading Cable Room
- Diesel Generator Building
- Electrical Switchgear Room
- Battery Room
- Pump House
- Radioactive Waste Buildings
- Personal Facilities

According to ASHRAE 50, chapter 28, section 4.4 the following HVAC characteristics are in these areas [6]. The **auxiliary building** is next to the reactor and holds safety and auxiliary (excess) equipment for the reactor [11]. These A/C units are one through-put systems and all exhaust air goes through a radioactive filtration system. The **control room** is brain of the plant and workers must be comfortable to work in the control room under all conditions, including meltdown in order to shut down the reactor. An HVAC consideration is that all potential hazardous fumes and fires need to be filtered out with excess smoke ventilation [6].

Control cable spreading rooms are above and below the control room and hold the conduit cables and trays [6]. **Electrical switch gear rooms** hold the electrical switch gears which includes fuses, circuit breakers, and other pieces of equipment that allow the electrical systems to be isolated and powered off as needed [12]. All objects radiate heat, especially electrical equipment. All of these rooms require mechanical ventilation where cool air consistently circulates in the room to keep the proper temperatures and humidities for the equipment to work properly [6]. The **diesel generator room** holds back-up generators for the plant. Since these machines require diesel there also needs to be space for the excess fuel. These generators are one of the many back-up safety protocols put in place so there can never be a power outage in the plant while the reactor is still active. Instead these back up systems are present to allow the necessary systems including the reactor to cool down and wait until power is restored [13]. The **battery room** holds the back up lead batteries as another precaution against a power outage. In some plants, if the diesel generators run out these batteries continue the shut down process for the plant [13]. These rooms must have extra ventilation for hydrogen that leaks out of the batteries during charging [6].

Personal facilities in most plants can operate with a normal HVAC system that includes a non-radioactive filtration system [14]. The **pump house** is responsible for the pipes and valves that pump water in the cooling loop. These pumps are very large and generate a lot of heat. Similar to the electrical rooms, these rooms require excess ventilation and cooling to ensure proper motor and pump function. The **radioactive waste buildings** like many buildings near the reactor have radioactive filtration systems [14]. Listing out these buildings and their functions, there are dozens of separate HVAC systems sprawled throughout a nuclear power plant. Due to the confinement in this paper, I'm concerning myself with only a couple of special considerations in HVAC systems in nuclear power plants.

4 Ventilating Excess Hydrogen from Battery Rooms

As previously stated, these plants have numerous back up facilities [6]. In most facilities there are dedicated rooms containing batteries for backup power. The purpose of the batteries is to power appropriate equipment to ensure proper shut down can occur in the event of a power outage [15]. The most common batteries in these facilities are lead acid batteries, specifically vented lead acid batteries [16]. Without delving into the chemistry, vented lead acid batteries produce hydrogen while charging. This hydrogen is an excess product of the chemical reaction and leaks out of the sides of the battery [16]. The issue is that hydrogen and oxygen are combustible. Once hydrogen reaches 4% of the concentration in the air it is extremely flammable, and combustion is inevitable. Therefore, building codes allow up to 1-2% of air to made of hydrogen [16, 6]. Pictured in Fig. 3 are two separate examples of battery rooms in power plants [17, 18].

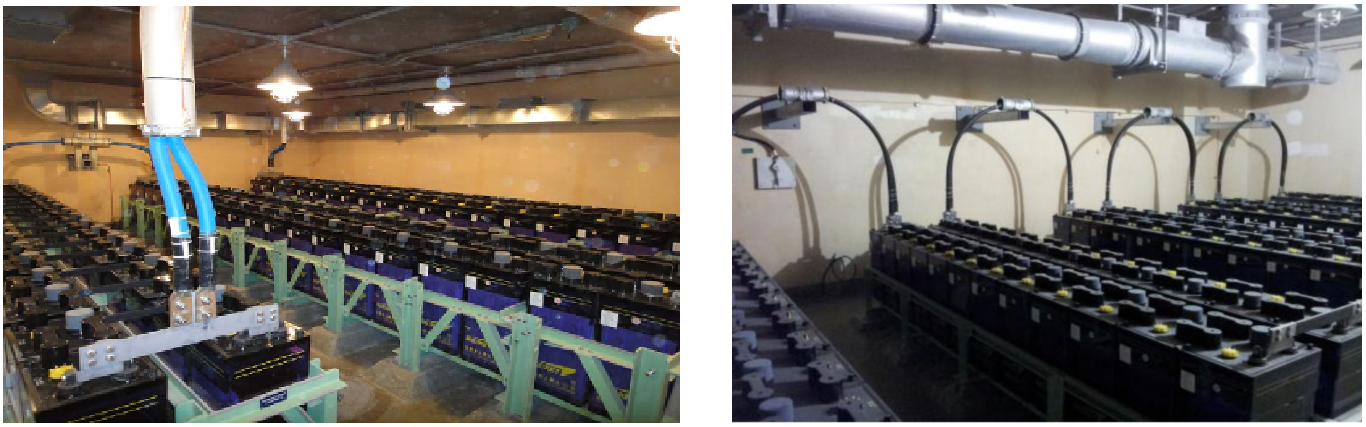


Figure 3: Two separate battery rooms in nuclear power plants [17, 18].

The solution to the excess hydrogen in the air is proper ventilation. There are two types of ventilation, natural and mechanical. Opening a window or a chimney are examples of natural ventilation. Obviously, there are no direct openings to the outside in a power plant. For safety reasons, as you don't want fumes released outdoors and you don't want easy infiltration from outside the facility. Therefore, mechanical ventilation is utilized. Hydrogen is 14x lighter than oxygen, so it rises quickly in a room. Therefore, it is advised that air enter at the floor of the room and leave through the ceiling of the room as shown in Fig. 4. This way any pockets of hydrogen don't build up in the corners or at the ceiling of the room [19]. Hydrogen is also clear and odorless, so the proper detectors are placed at the ceiling on the rooms. These rooms are typically small to prevent any cross drafts and allow the air to continuously flow in and out of the system [19]. This is a characteristic in both battery rooms shown in Fig. 3.

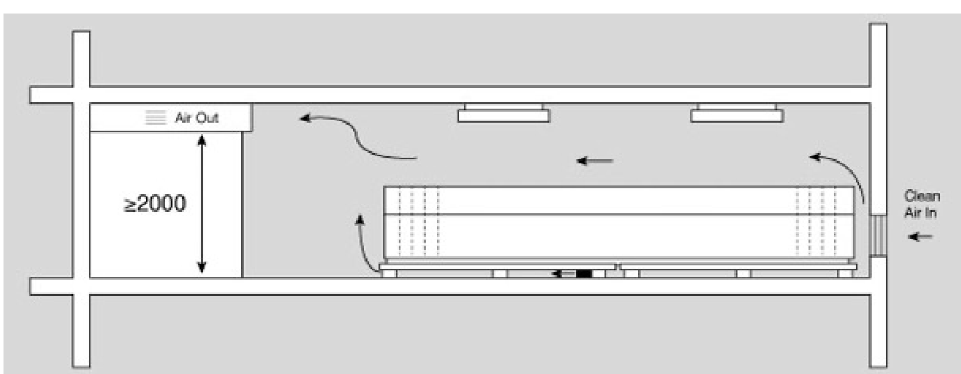


Figure 4: The flow of air through a battery room. Inlets are near the floor and outlets are at the ceiling [20].

Another concerning product of vented lead acid batteries is hydrogen sulfide which smells like rotten eggs [19]. As one can imagine, this makes for a nearly uninhabitable work area [21]. Like hydrogen gas the solution is a proper ventilation system that cycles clean air constantly. Hydrogen sulfide is heavier than hydrogen gas, so it sits on top of the batteries as opposed to immediately rising towards the ceiling [19]. To ensure proper ventilation multiple air outlets are placed directly over the batteries [22], such as the configuration in Fig. 5. The green box is an air inlet and the red boxes are outlets [22]. Here, multiple smaller outlets are placed directly above the batteries. In some cases these rooms also have smoke hoods in case of a fire [19]. Having a small room also helps properly ventilate both gases. Due to the concern of hydrogen gas and hydrogen sulfide, no air in these rooms is recirculated. Instead, the delivery systems are one-through put systems [6]. Another interesting HVAC requirement in these spaces are the temperature and humidity guidelines. Batteries work "optimally" in the proper environment. According to ASHRAE 50, these rooms should be kept at 70 to 80 degrees Fahrenheit.

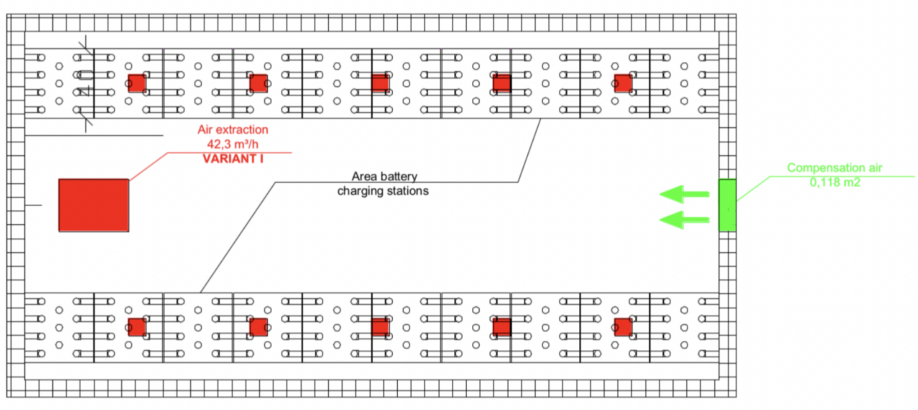


Figure 5: A diagram detailing the inlet and outlet of vents in a battery room. The outlets are directly above the batteries to ensure there is no build up of gases such as hydrogen sulfide [22].

At the bare minimum, the exhaust should allow at least five air changes per hour [6]. An air change refers to the air in a room being completely replaced, therefore the air needs to be replaced at least five times in a battery room per hour according to ASHRAE 50 [23]. Depending on the number and model of batteries the air changes ($\frac{m^3}{hr}$) can be calculated with an Equation such as Eq. 1.

$$Q = 0.05(n)(I) \tag{1}$$

where n is the number of batteries in a room and I is the value of current from table EN 50272-2.

EN 50272-2 is ”the safety requirements for secondary batteries and battery installation”. This is a European standard but a similar table and equation can be used in the United States. [24].

5 Radioactive Filtration Systems

All the HVAC systems input, circulate, and eventually release the air back into the environment. Depending on the area, the air entering the rooms are either a combination of fresh air and recirculated air or entirely fresh air. Regardless, the air going through these areas is eventually released into the environment including areas directly connected to the reactor. Here, the concern is iodine, carbon, and hydrogen being released into the environment. The release of radioactive iodine is linked to thyroid cancer [25]. This is one of the major concerns from the fallout of Fukishima [25]. Any leakage of radioactive materials is devastating to a local environment and community. Radioactive materials could leak into the air, soil, and waterways such as those used for a cooling reservoir. An example of these events is Three Mile Island in Pennsylvania.

Therefore, how can HVAC systems release this air safely into the environment? The solution is a complex filtration system coupled with the proper electrical systems for powering these filters. Figure 6 details a filtration system. The IEEE or institute of electrical and electronics engineers and the NRA or the nuclear regulatory commission both require Class 1E buses to power this equipment [26]. These are electric systems designed specifically for powering safety related systems in a nuclear facility.

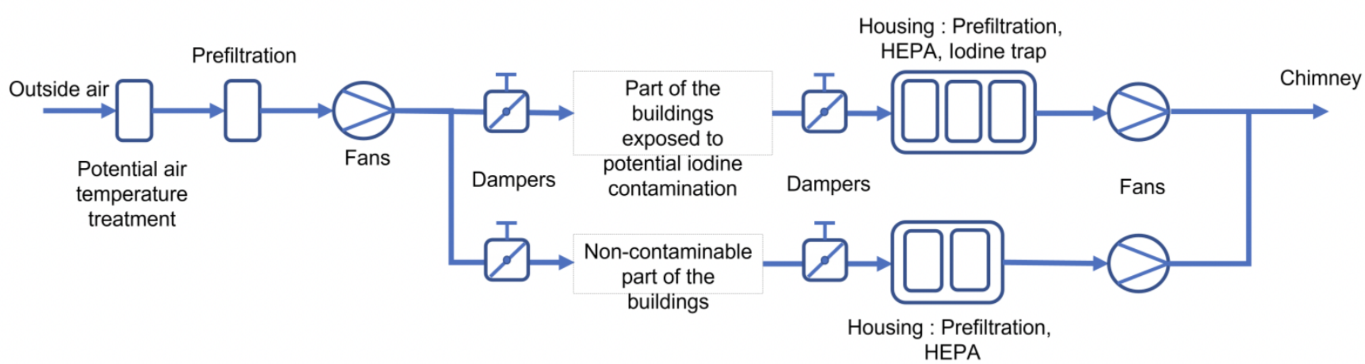
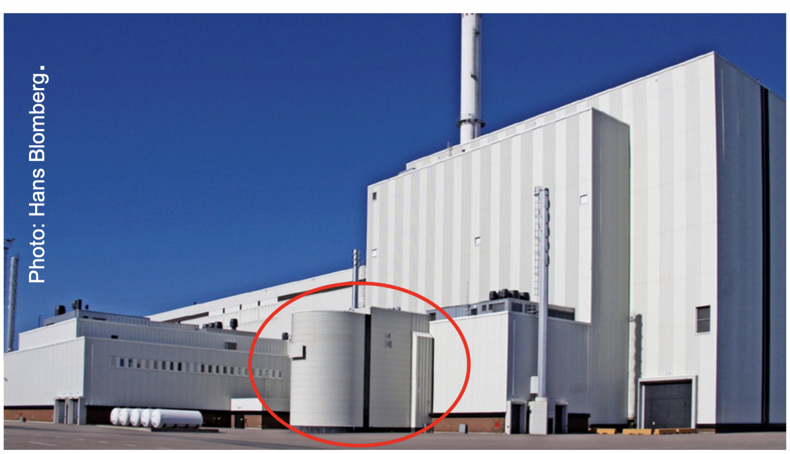


Figure 6: Air filtration system in a nuclear power plant. A facility contains both non-radioactive and radioactive filtration systems [14].

Outside the plant, outside air enters an air handling unit where it can be heated or cooled by equipment inside the air unit. Then it goes through pre-filtration to filter out large particles. A demister separates the vapor from the liquid, allowing the vapor to pass. A separate process occurs for the radioactive liquid. An electric heater is also used on incoming air to reduce the relative humidity, usually from 100% to less than 70% [6]. This causes more of the air to evaporate. HEPA stands for high-efficiency particulate air filters and are widely known as the best particulate filters available. The most efficient HEPA filters can theoretically filter out 99.97% of particles greater than 0.3 microns [27]. A carbon filter traps carbon particles through absorption. These filters cause the radioactive material to desire (in a chemical sense) to stay on the filter, allowing cleaner air particles to pass through. They do a similar job for iodine as HEPA filters do for particulate matter. (ULPA filters capture even smaller particulate matter.) There are also dampers at the entrance and exit of the system which control the flow rate of air through the system. Of the entire process the HEPA filters are key for filtering radiation. These magnificent pieces of equipment were born from the Manhattan project for the exact reason of filtering radioactive air particles [28].

5.1 Industry Examples

These systems are used daily, but there are certain pieces of equipment only used in emergencies. Such is the case with the Westinghouse FILTRA-MVSS pictured in Fig.7.



FILTRA-MVSS (circled) at Forsmark 3, Sweden

Figure 7: Circled in red is the Westinghouse FILTRA-MVSS [29].

This system depressurizes the containment building by releasing air into the atmosphere [29]. The purpose of the system is to filter out highly radioactive air, keeping nearly 99.9% of the radioactive particles "contained or filtered" in the structure [29]. The system is utilized in the worst case emergencies including a core meltdown. It is meant to operate on a 24 hour shut down schedule. The image in Fig. 7 is a screenshot from Westinghouse's nuclear services PDF on these systems. This particular plant is in Sweden but these systems can be attached to the two most common types of nuclear power reactors including PWR [29]. From the image, the reader can see the vessel is large in size. It is hard to believe this much space is taken up by a single back up system, that hopefully never has to be used for an emergency situation.

Picture below in Fig. 8 is a single filtration system available at Camfil. Camfil is an engineering company that produces air filters [30]. This machine filters are at 6500 cfm or cubic feet per minute. As described in Fig. 6 this filtration system includes fans, dampers, air heaters, pre-filters, HEPA filters, and more [31].

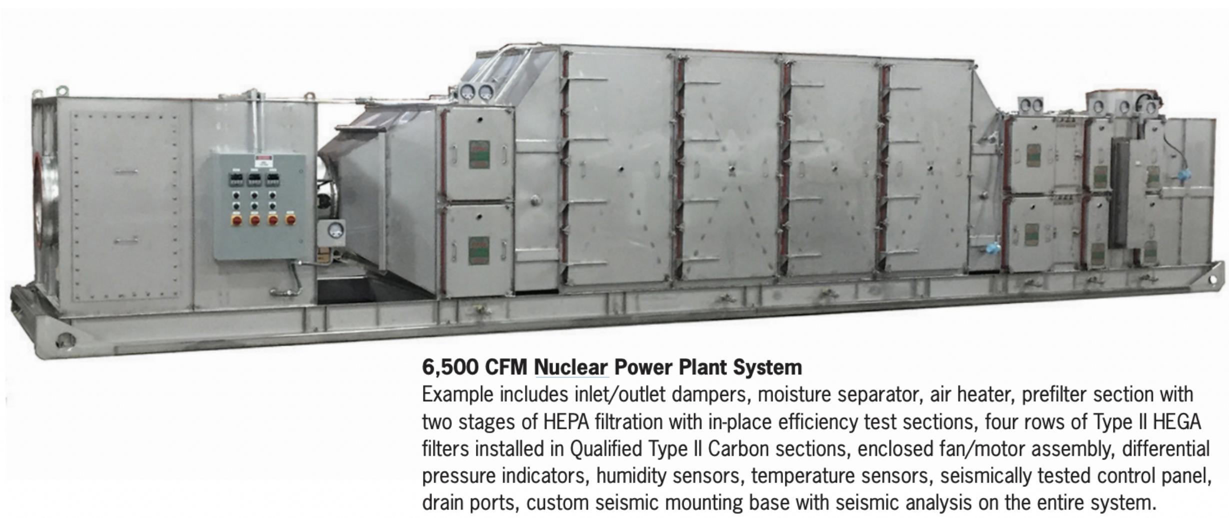


Figure 8: This is an image from Camfils specialty product pamphlet. Per the description in the image, this single system contains the filtration system described previously [31].

6 Conclusion

This paper examines a few special considerations for HVAC systems in a nuclear power plant. When designing for a nuclear power plant, the two primary concerns are ventilating excess heat and potentially harmful fumes from buildings, as well as filtering out radioactive particles before releasing circulated air into the environment. Though, each building has its own unique requirements for HVAC systems depending on its exposure to radioactive particles, equipment, expected personnel work environment, and level of criticality to the plants operations. Buildings on the nuclear island (buildings that influence the reactor) require specialized safety systems such as the MVSS filter for safe and up to code operation. Certain areas such as the control room, battery room, and containment building are one-through put HVAC systems. Essentially all filtration systems require some HEPA filters for the radioactive particles. Though, areas such as the personal facilities can operate with systems found at a typical commercial building. In areas with large pieces of mechanical equipment including pumps and turbines, as well as large amounts of electronics, fans must cool these systems for proper performance. Overall, this paper only touches the surface of a few of these considerations. There are still individual complex systems, such as the Camfil 6500 CFM Nuclear Power Plant Filtration system, scattered throughout a plant.

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